



HEAVY ION INTERACTIONS AT RELATIVISTIC ENERGIES

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INTRODUCTION

Studies of heavy ion interactions in the field of high energy nuclear physics have been possible to perform ever since the discovery in 1935 of a component of matter in the cosmic radiation. For more than two decades the experimentalists in this field made use of the cosmic radiation as beam and nuclear reactions were studied in the laboratory.

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In August 1971, a new era in the study of heavy ion experiments took place. The first time, through the use of the heavy ion beam, with charge to mass ratio $1/2$, could from this date be accelerated to relativistic energies in the heavy-ion-beam facility of the Lawrence Berkeley Laboratory. Later improvements of the Bevatron made it possible to accelerate even heavier ion species, such as ^{40}Ar , to energies up to 2.1 GeV/nucleon.

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INTRODUCTION

Studies of heavy ion interactions in the field of high energy nuclear physics have been possible to perform ever since the discovery in 1948 of a component of nuclei in the cosmic radiation. For more than two decades the experimentalists in this field made use of the cosmic radiation as beam and nuclear emulsions as target and detector.

In August 1971, a drastic improvement in the status of heavy ion experiments took place. Beams of ions, ^2H through ^{20}Ne , with charge to mass ratio $1/2$, could from this date be accelerated to relativistic energies in the Bevatron-Bevalac facility of the Lawrence Berkeley Laboratory. Later improvements of the Bevatron made it possible to accelerate even heavier isotopes, such as ^{40}Ar , to energies up to 2.1 GeV/nucleon.

Counter detector systems including magnetic spectrometers have been used in inclusive heavy ion experiments to measure reaction- and fragmentation cross sections as well as momentum distributions of beam fragments and produced mesons^[1]. A search for evidence of hypernucleus production has been performed by using spark chambers. Track detectors such as emulsions, AgCl crystal detectors, and streamer chambers have been used to study the complete disintegration of the interacting nuclei^[2,3].

Plastic foil detector experiments have given us information concerning an extremely large emission of fragments with energies below the Coulomb barrier in relativistic heavy ion reactions^[4].

A new type of target-detector system with metallic wires embed-

ded in emulsions has been developed at the Department of Cosmic High Energy Physics in Lund^[5]. An exposure of this emulsion type with tungsten wires, to a 2 GeV/nucleon ^{40}Ar beam from the Bevatron is planned for this year. This type of experiment opens up new and fascinating possibilities of studying all charged reaction products from relativistic heavy ion reactions with well-defined target nuclei.

Several theoretical models for heavy ion interactions have been suggested. In the GeV region the interacting nuclei are often treated as Fermi gases of nucleons. The de Broglie wave length of nucleons at this energy is small compared with the average spacing of nucleons in a nucleus. It is therefore assumed that the target nucleus appears to the projectile as a gas of independent nucleons.

The models often predict two or three steps in the reaction scheme. The first step can be regarded as a superposition of nucleon-nucleon or perhaps nucleon-cluster scattering^[6]. If the nucleus is large enough, the scattered particles may collide again and perhaps develop a cascade of hadron-hadron collisions. In some statistical models it is assumed that the momentum transfer in the first step is small and only reflects the intranuclear motion of the nucleons^[7,8]. Most of the models predict a transfer of excitation energy to the residual nucleus. The deexcitation of the nucleus is often treated as evaporation of particles from a gas in equilibrium with a certain temperature. Sometimes an intermediate reaction step is assumed to occur at the time between the fast step and the evaporation. This step has been regarded either as preequilibrium emission or as an effect of the reabsorption of nucleons released in the first reaction step^[9].

These statistical models are successful in explaining the main features of the particle emission in peripheral heavy ion reactions.

Recent reports from track detector experiments have, however, shown that the models, described above, fail to explain results from heavy ion reactions with small impact parameters. One interesting suggestion is that conditions for developing a nuclear shock wave should be fulfilled when a light nucleus with supersonic velocity interacts with a heavy target nucleus^[10,11]. When the density perturbation, perhaps in the form of a Mach cone, reaches the nuclear surface, particles are emitted at right angles to the front. Some experimental angular distributions of light particles indicate that shock wave emission may exist in head-on collisions, but it is still too early to bind oneself to this model.

CONTENTS OF THE THESIS

The thesis is based on investigations published in the following articles:

- I. Fast Helium Nuclei in Interactions Induced by Very Heavy Nuclei. Z. Physik 268, 1 (1974).
(In collaboration with R. Kullberg and I. Otterlund).
- II. Pion and Proton Emission in Interactions Induced by Relativistic Nuclei with $Z \geq 12$. Z. Physik A272, 159 (1975).
(In the collaboration with R. Kullberg and I. Otterlund).
- III. Transverse Momentum Distributions of Multiply Charged Fragments in ^{16}O -Emulsion Nucleus Interactions at 2.0 GeV/Nucleon. LUIP-CR-75-02, submitted to Lettere al Nuovo Cimento. (In collaboration with R. Kullberg and I. Otterlund).

IV. Interactions of 2 GeV/Nucleon ^{16}O with Light and Heavy Emulsion Nuclei. LUIP-CR-75-14, submitted to Physica Scripta.

(In collaboration with R. Kullberg).

Reports have been given at the following conferences:

The 5th International Conference on High Energy Physics and Nuclear Structure, Uppsala 1973.

The Conference of the Swedish National Committee for Physics, Göteborg 1975.

The 6th International Conference on High Energy Physics and Nuclear Structure, Santa Fe/Los Alamos 1975.

The 14th International Cosmic Ray Conference, München 1975.

The 8th European Conference on Physics and Chemistry of Complex Nuclear Reactions, Frostavallen/Lund 1975.

The experiments described in the above articles reflect the transition from the use of cosmic ray nuclei to accelerated beams of heavy ions as projectiles. Papers I and II are based on reactions induced by nuclei from the cosmic radiation with charges ≥ 12 and energies ≥ 1 GeV/nucleon. Papers III and IV present experimental results from interactions induced by 2 GeV/nucleon ^{16}O accelerated in the Berkeley Bevatron. The detectors used are nuclear emulsions of different types. In the first investigation an electron-sensitive emulsion (Ilford G5) was chosen. This implies that the meson component of the reaction products could be studied. On the other hand, no charge resolution of particles producing short range tracks could be received. In the second investigation a less sensitive emulsion

type (Ilford K2) was used. Here charge resolution was possible for particles producing tracks with very small ranges in the emulsion. In both investigations a distinct separation between interactions in the three emulsion components H, CNO and AgBr was obtained.

The emission of high energy helium nuclei in reactions induced by heavy nuclei has been studied in Paper I. The energy and angular distributions are not reproduced by statistical heavy ion reaction models. The energy spectra, integrated over all angles, has a power law form, $E^{-\alpha}$, in the high energy region. The exponent α is 1.8 ± 0.1 whereas a quasi-elastic $p\text{-}^4\text{He}$ scattering calculation predicts $\alpha \approx 7$. The ratio between the frequencies of helium nuclei in nucleus-nucleus and proton-nucleus collisions is ~ 20 in the high energy region compared with a ratio ~ 2 for the total helium emission. It is moreover obvious that the emission of energetic helium nuclei increases rapidly both with increasing mass and increasing degree of disintegration of the target nucleus.

Paper II deals with the emission of protons and pions in the same experimental sample as in Paper I. The low energy part of the protons has the same evaporation characteristics as in nucleon-nucleus collisions. In the high energy region there is an excess of protons emitted in the forward direction compared to nucleon-induced reactions. The pion multiplicity depends on the mass and degree of disintegration of target nuclei in a manner which indicates that many nucleons in the incident nucleus interact in a cooperative fashion. The width of the pseudo-rapidity distribution ($\sim \log_{10} \theta$) of pions + relativistic protons is remarkably small and almost independent of the degree of disintegration of the nuclei. In events with an extremely large

pion production and large disintegration of the nuclei there is still a small width, $\sigma = 0.46$, in the $\log \theta$ distribution. Furthermore, this distribution fits well with nucleon-nucleon scattering but deviates from the results of proton-nucleus interactions which show much broader distributions.

Paper III presents transverse momentum distributions of multiply charged relativistic fragments emitted in 2 GeV/nucleon ^{16}O reactions in emulsion. This experiment mainly confirms the Gaussian momentum distributions, with small widths ($50 \leq \sigma \leq 200$ MeV/c), found in the spectrometer measurements in Berkeley and interpreted by statistical models. A wider momentum distribution extended to several hundred MeV/c is, however, overlapped on the Gaussian curve. The importance of this wider distribution increases with decreasing fragment mass, and is especially large in events where the ^{16}O nucleus is disintegrated into one light fragment and nucleons.

In Paper IV a description is given of energy loss measurements, particle identification and target nucleus determination in low-sensitive emulsions. The reaction cross sections of ^{16}O reactions in the emulsion target components H, CNO, and AgBr agree well with theoretical Glauber scattering calculations. Energy-, angular- and transverse momentum distributions of non-relativistic protons, helium- and lithium nuclei indicate differences in the reaction mechanisms for reactions with light and heavy target nuclei.

In CNO interactions, nucleon-nucleon scattering can explain the main part of the proton emission. Very little momentum is transferred to multiply charged fragments in agreement with statistical model predictions.

In AgBr reactions the results indicate that nucleon-nucleon scattering is followed by evaporation from an excited residual target nucleus. The broad transverse momentum distribution and the high degree of isotropy in the angular distribution of high energy helium nuclei remain to be explained. Some indications, presented in this paper, suggest that these helium nuclei as well as a part of the high energy protons in head-on events may be emitted as a result of violent phenomena such as the propagation of a shock wave through the nucleus.

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